EXPLORATION OF THE "DAMAGE LIMIT" LIGHT FLUX FOR GRAZING INCIDENCE LIQUID METAL MIRRORS

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ABSTRACT

One definition for the "damage limit" of a liquid metal surface used as a final optic for laser fusion power plants is the maximum energy flux that the liquid metal can withstand without any resulting spallation. Some preliminary calculations were performed by Moir to roughly estimate the damage limit by imposing the restriction of a 200°C surface temperature rise. Here, new 1D calculations, that account for hydro-motion on the compressible times scales, are presented, along with revised estimates of the damage limits for liquid aluminum, mercury, and sodium. Slow compression time scales (~20 ns) produced negative pressures in the liquid film on the order of MPa, and fast ignition time scales (~10 ps) yielded GPa pressures for the laser energy densities set out by Moir. For Na and Al the peak energy densities normal to the beam on the order of 5 to 10 J/cm^2 were acceptable for fast ignition. Some experimental data on the generation and damping of surface waves resulting from surface ablation recoil is also presented, where large waves are seen damp out after about 50 ms following the laser pulse.

I. INTRODUCTION

The Grazing Incidence Liquid Metal Mirror (GILMM) is a potentially attractive, but highly speculative, concept for laser fusion power plants where a slowly moving liquid metal film is used as the reflective surface for grazing incidence final focusing mirrors. For standard Grazing Incidence Metal Mirros (GIMMs), laser light grazes the mirror surface at up to 85° from normal. Because the area of surface that comes into contact with the laser is increased, the energy flux on the reflective surface is reduced. This enables the mirrors to reflect high energy density beams, since the mirrors only "see" the reduced energy flux. However, small flaws and surface imperfection in the GIMMs can locally see the full normal energy flux, and local melting/solidification, and crack propagation, can occur, resulting in the growth of flaws[1]. The idea of the GILMMs, originally proposed and analyzed by Moir[2], is that liquid surface tension will "heal" any small ripples and surface imperfections so that a very smooth surface is presented to the incident laser beam in each pulse. If made to work to their potential, the projected life span for a GILMM can be more than 30 years.

Despite the potential advantages of the GILMMs, there are certainly many issues concerning their feasibility. Examined here are issues related to maintaining a smooth liquid surface and macroscopic ejected material, and minimizing surface rippling due to any impulse imparted by the laser beam effects. Differential heating (as a function of depth) and surface ablation from the pulsed laser beam heating can effectively launch pressure waves into the liquid film. These pressure waves can reflect from the liquid free surface to create tension in the liquid – possibly leading to its fracture or *spall*. Additionally, close to the edge of the beam, differential pressurization can generate large surface waves, due to the absence of any pressurization of the liquid film outside of the beam area. Both of these phenomena can effectively set a limit on the amount of laser energy that can be absorbed at the liquid surface – what we term here as the "damage limit light flux" or just "damage limit."

II. PRELIMINARY DAMAGE LIMIT CALCULATIONS

The pressure pulses launched into the liquid surface of a GILMM during heating by the laser beam can reflect into tensile waves large enough to result in spallation, a planar separation of the liquid from the bulk. The damage limit for a GILMM, based on spallation, is defined by Moir[2] as the laser energy flux, normal to the beam direction, at which spallation in the liquid metal will occur. The spallation phenomenon in liquids, according to homogeneous nucleation theory, is a result of massive nucleation in the liquid due to large tensile stresses applied at high strain rates ($>10^6$ s^{-1})[3]. Seen in a different light, spall occurs when the negative pressures exceed the liquid's ability to hold itself together.

Moir[2] performed calculations to model laser energy deposition in the liquid metals for laser fusion applications. Specifically, he chose a laser wavelength of 0.35 micron operating at 85° grazing incidence. He also chose two representative pulse durations indicative of slower compression (20 ns) and fast ignition (10 ps). His preliminary calculations for surface temperature rise were performed using the following approximate relation from the literature:

$$\Delta T = \frac{2(1-R)q_{beam}}{k}\sqrt{\frac{at_p}{p}} \qquad (1)$$

where α, R, k, t_p and q_{beam} are respectively the LM thermal diffusivity, reflectivity, and thermal conductivity; and the laser pulse length and power density incident on the liquid surface. In order to get an initial estimate to the damage limit, he assumed a maximum allowable surface temperature rise of 200°C for a variety of liquid metals, of which the top candidates were Al, Na, and Hg (summarized in Table 1). The peak pressure that would occur in the liquid was estimated using the Gruneisen coefficient in the following equation $p = \Gamma E/V$, E is the total deposited energy, V is the volume where energy is deposited and Γ is the Gruneisen coefficient. The calculated peak pressures based on the 200°C surface temperature rise were on the order of hundreds of MPa to GPa – which is in the range of the theoretical spall strength of liquids. But Moir notes that, since the above equation was an approximation that neglected hydrodynamic motion, it can be viewed as a worst case guess. Therefore, more analysis will be required to determine whether there is the danger of spallation.

III. ABLATOR CODE ANALYSIS

The ABLATOR code[4], which stands for Ablation By Lagrangian Transient One-Dimensional Response, was initially developed by Anderson to determine material response to X-rays in IFE chambers. It can model the compressible hydrodynamic motion, due to isochoric heating, and subsequent rapid expansion. The code also has an integrated nucleation model, which can be used to predict liquid spall. For the analysis here, a nucleation rate of 10^6 bubbles/s/m^3 was chosen as the threshold rate for spallation, where liquid spall is assumed to occur when the maximum nucleation rate reaches this value. Additional details of the analysis and results reported here are available in Quan[5].

Three liquid metals, Al, Na, and Hg were first analyzed to determine whether Moir's damage limit estimates would result in spallation. The absorbed energy flux for Moir's damage limits were used as the deposited energy input to the code. The damage limit results for both slow compression and fast ignition are summarized in Tables 1 and 2. The peak pressures produced for slow compression were approximately three orders of magnitude below Moir's worst case predictions. In the case of fast ignition, the predicted pressures were approximately the same order of magnitude, but still below Moir's. The nucleation rates were not high enough for liquid spall in any of the cases analyzed.

The ABLATOR code was then used to produce a new estimate for damage limit for the two representative pulse lengths. Again using the threshold nucleation rate of 10^6 bubbles/s/m^3, the input energy flux could be increased until the threshold value is reached. This analysis was performed for the three candidate liquids and the results are shown in Table 3 for the fast ignitor pulse. Al exhibited the best performance with approximately 10 J/cm^2 allowed beam energy in the 10 ps pulse – twice that of Na (example pressure, temperature and nucleation rate profiles depicted in Figure 1) and an order of magnitude better than Hg. If one assumes a total fast ignitor beam energy on the order of 100 KJ[6], then only 1 m^2 of mirror area is required for an Al film, if spallation is taken as the limiting factor.

Table 1: Comparison of Moir's calculations for damage limit with ABLATOR results for slow compression

Liquid Metal	Method	Absorbed Energy Flux [J/cm^2]	Damage Limit [J/cm^2]	Surface Temperature Rise [K]	Peak Pressure [MPa]
Al	Moir	0.064	106	200	2100
	ABLATOR	0.064	-	316	1.34
Na	Moir	0.025	57	200	160
	ABLATOR	0.025	-	62	0.34
Hg	Moir	0.01	6	200	300
	ABLATOR	0.01	-	187	0.75

Table 2: Comparison of Moir's calculations for damage limit with ABLATOR results for fast ignition

Liquid Metal	Method	Absorbed Energy Flux [J/cm^2]	Damage Limit [J/cm^2]	Surface Temperature Rise [K]	Peak Pressure [MPa]
Al	Moir	0.00143	2.36	200	2100
	ABLATOR	0.00143	-	307	0.48
Na	Moir	0.00057	0.16	200	160
	ABLATOR	0.00057	-	50	0.14
Hg	Moir	0.000224	0.30	200	300
	ABLATOR	0.000224	-	165	0.20

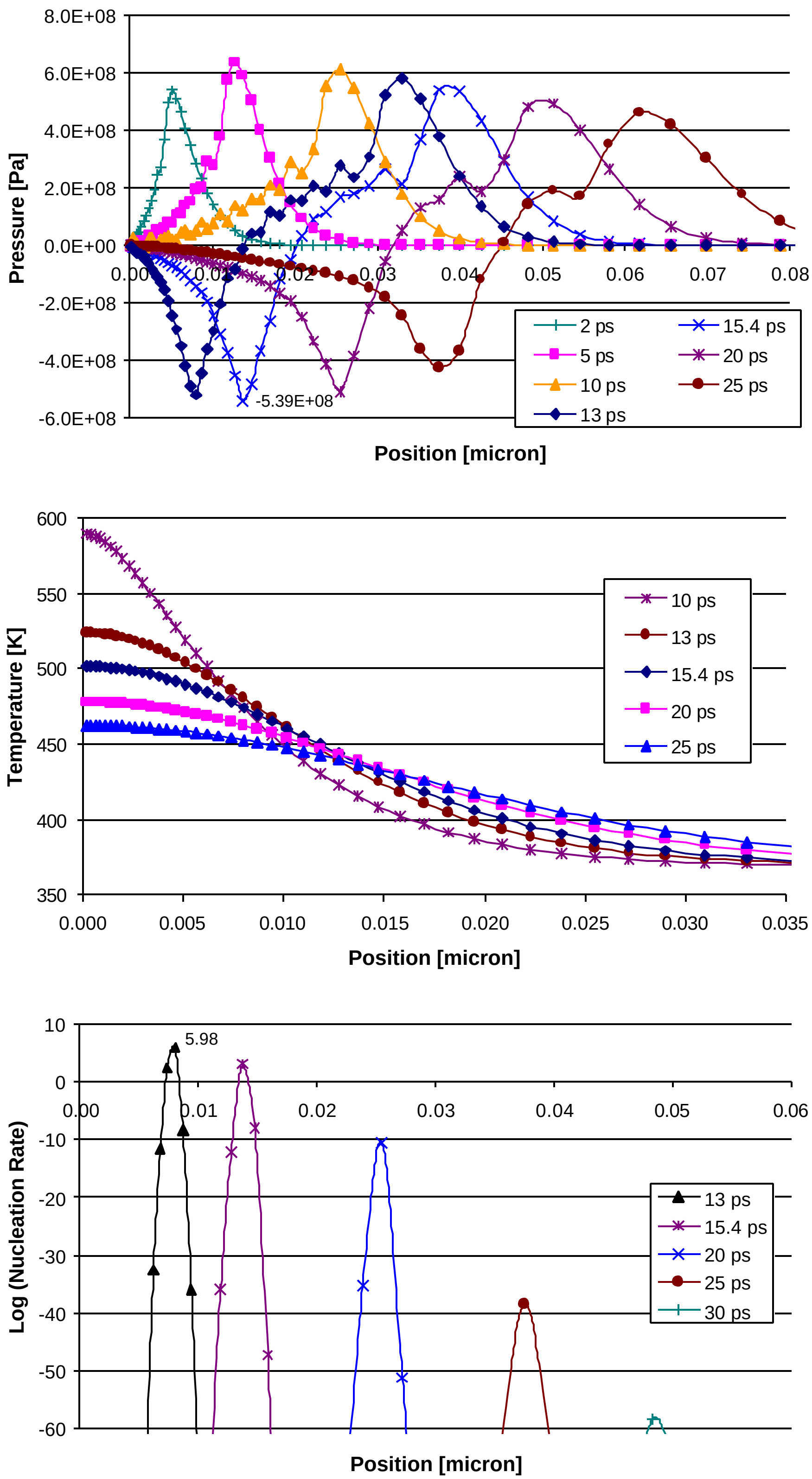

Figure 1. Pressure, temperature and nucleation rate profiles calculated with ABLATOR for a sodium film subjected to a 10 ps, 0.35 micron laser pulse at 85° from normal incidence and 5.35 J/cm^2 normal to the beam.

Table 3: New Damage Limit Estimates for Fast Ignition (10 ps) Time Scales

Liquid Metal	Melting Point [K]	Damage Limit [J/cm^2]	Spall Pressure [GPa]	Spall Temp. [K]
Al	933	10.23	1.47	1720
Na	371	5.35	0.52	480
Hg	234	0.84	0.40	1110

Spallation in the case of fast ignition occurs as a result of a combination of high local temperature and large tensile stresses leading to massive nucleation. The site of the predicted spall is not actually the depth where the maximum negative pressure occurs, but is instead a site where high temperature lowers the spall strength (increases the nucleation) to the point where spall is indicated. The depth at which spall occurs is quite shallow under these conditions. For the sodium case depicted in Fig. 1, the spall point is around 0.01 micron into the film, only a few hundred atomic layers (casting some doubt on the applicability of these continuum calculations).

The results for slow compression are not shown because no value for damage limit was found. The largest peak negative pressures achieved were not enough to cause significant nucleation. Even as the energy of the beam was increased, there came a point where the peak negative pressure began to decrease. This behavior was seen for all three liquid metals. Although we do not rule out the possibility that this is an artifact of the numerical treatment at the liquid surface, it is hypothesized that this behavior occurs because the pressure at the liquid surface remains high due to rapid surface vaporization (the surface is not truly “free”). And so reflected waves are not completely inverted, but partially transmitted into the gas. This surface effect acts in concert with the rapid relief of pressure due to acoustic wave propagation into the bulk which occurs over the relatively long slow compression pulse duration. Therefore, it is concluded that the liquid metals will not spall homogeneously for slow compression. Since strain rates for slow compression are on the order of 10^5-10^6 s^{-1}, the possibility of liquid spall due to heterogeneous fracture is still present.

VI. BEAM EDGE EFFECTS

Rapid surface ablation from the laser heating will cause a recoil impulse to be delivered to the liquid surface. Near the edge of the beam, the liquid surface will have a region that is heated sitting very close to an unheated region. The mismatch in the surface pressure during the laser pulse can set up surface waves that can potentially destroy the optical quality of the surface for subsequent laser shots. We call this “edge effect” and it will theoretically have its own associated damage limit light flux. This damage limit will be highly design depended, as the size of surface disturbance allowed following the shot will be determined by the damping characteristics of the flow. That beam edge effects can indeed be significant is seen in some preliminary experimental results on liquid Hg, shown in Fig. 2. The absorbed energy density in this experiment is 100 times larger than what was recommended by Moir, based on a 200°C surface temperature rise, and also the wavelength of the laser is 3 times longer, causing a more shallow heat deposition and more surface heating. In addition, the ratio of the the liquid depth to the beam energy fall-off length is much larger than would be seen in a real laser fusion system. But even in this extreme case, the large wave died out to visual inspection in 50 ms.

V. CONCLUSIONS

In comparing Moir’s worst case estimates with ABLATOR code results, it can be concluded that Moir’s values were indeed very conservative estimates of damage limit. The new damage limits for Al, Na, and Hg for the fast ignition pulse were found to be 10.23, 0.84, 5.35 J/cm^2, respectively. Although Al has the highest value for damage limit, Na may be a better candidate because it has a significantly lower melting point and typical oxides tend to be denser than the metal itself, causing them to sink. No specific values for damage limit were found for the slow compression pulse, due to the fact that the time scale was long enough for liquid expansion to relieve the high pressures in the liquid and surface mass vaporization kept surface pressure high. The nucleation rates for this case were not high enough to result in liquid spall, according to the models used in these calculations. Similarly, waves setup from beam edge effects damped rapidly, even for extreme energy density cases.

Additional work on flowing liquid film stability and wave propagation and damping behavior, as well as a serious study of the beam quality of the reflected beam, will be required to fully validate this concept. However, the initial work reported here in encouraging.

ACKNOWLEDGMENTS

This work was supported by DOE Grant DE-FG03-94ER54287. The authors have benefited greatly from informative discussions with R. Moir.

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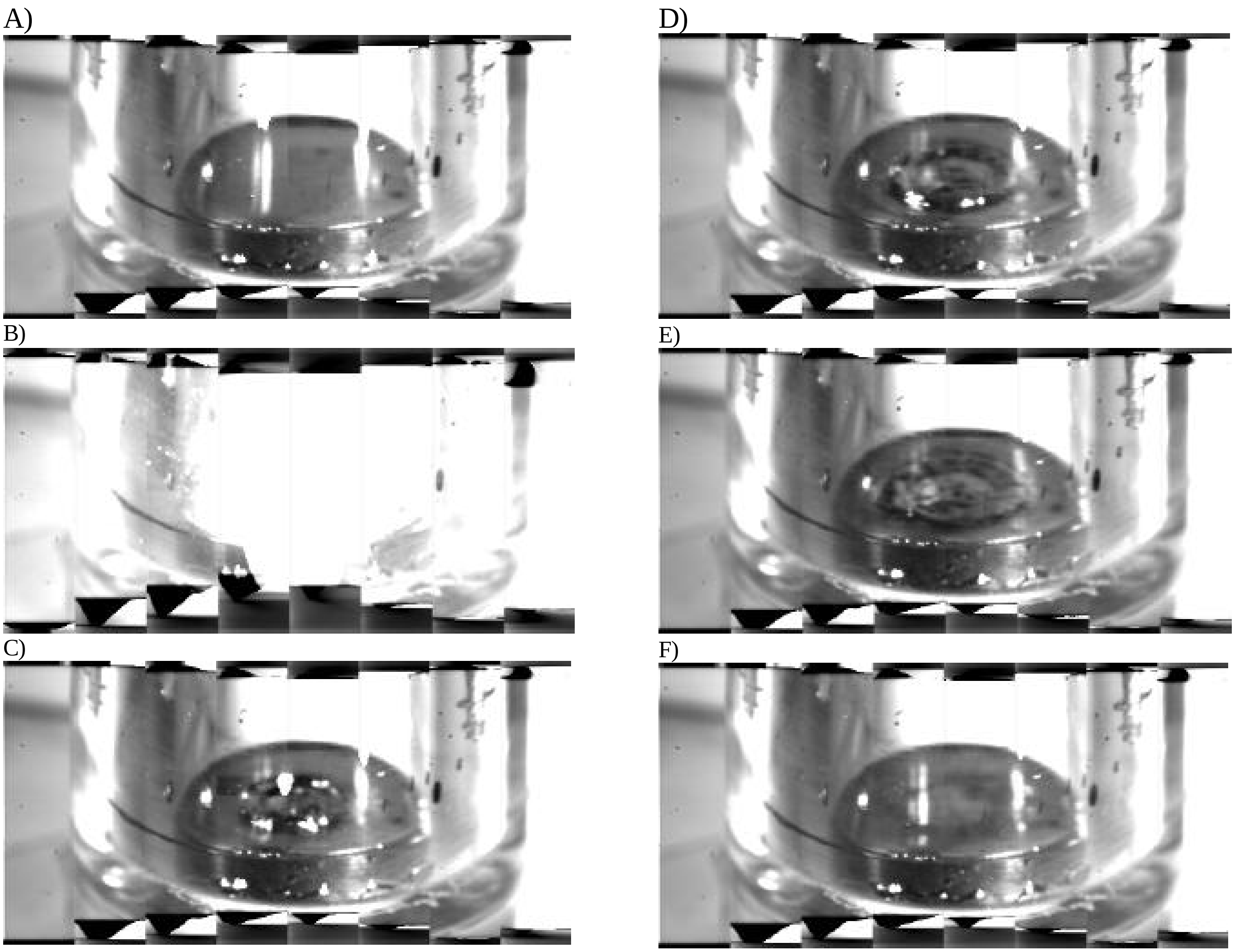

Figure 2: Waves generated by high energy density laser on Hg mirror surface.
A) Hg surface before the laser pulse. Total Hg surface area is 158 mm^2, thickness of Hg film is 1 mm
B) Hg during laser pulse, strike area is ~9.6 mm^2, angle of incidence is 14°, laser beam energy is 0.68 J @ 1µm wavelength, energy density normal to beam is ~7 J/cm^2, estimated absorbed energy density is ~1 J/cm^2
C) Hg surface 1ms after the laser pulse. Wave amplitude estimate 0.81 mm
D) Hg surface 2 ms after the laser pulse. Wave amplitude estimate 0.38 mm
E) Hg surface 3 ms after the laser pulse**.** Wave amplitude difficult to measure
F) Hg surface 57 ms after the laser pulse. No motion visibly detectable